Application for United States Letters Patent

for

Color Interpolation for a Four Color Mosaic Pattern

by

Tinku Acharya

Edward J. Bawolek

Ping-Sing Tsai

and

John J. Bean

Seth Z. Kalson
Intel Corporation

Express Mail: EL164804357US

Field of Invention

The present invention relates to imaging, and more particularly, to a four-color mosaic tiling pattern and color interpolation.

Background

5   A simplified cross sectional view of an imaging system is illustrated in Fig. 1. Optical system **102** focuses electromagnetic radiation onto a focal plane, which may be taken as Color Filter Array (CFA) **104** and pixel sensor array **106**. The CFA is usually deposited over pixel sensor array **106** by photo-lithographic techniques well known to the semiconductor industry. Pixel sensor array **106** is an array of pixel sensors, where in

10   general, a pixel sensor is any sensor which absorbs radiation and provides a signal indicative of the absorbed radiation. Pixel sensor array **106** may be, for example, an array of charge coupled devices (CCD), or an integrated array of CMOS (Complementary Metal Oxide Semiconductor) pixel circuits. A pixel circuit may comprise a photo diode, where photons absorbed by the photo diode generate electron-hole pairs, along with additional

15   circuits to provide an electrical signal, either a voltage or current signal, indicative of the number of photons absorbed by the photo diode. Photons incident upon various pixel circuits are pictorially indicated by **108**.

     The spectral content of electromagnetic radiation focused onto a focal plane depends upon, among other things, the imaged subject, the illumination of the subject, the

20   transmission characteristics of the propagation path between the imaged subject and optical system **102**, the materials used in optical system **102**, as well the geometric shape and size of optical system **102**. For consumer imaging systems, the spectral range of interest is the visible region of the electromagnetic spectrum.

     The CFA is an array of filters, usually contiguous and deposited over pixel sensor

25   array **106** so that each pixel sensor is substantially sensitive to only the electromagnetic radiation passed by one filter. (A filter in the CFA may actually be a composite filter manufactured from two or more filters, so that the transfer function of the resulting filter is the product of the transfer functions of its constituent filters.) Each filter in the CFA passes electromagnetic radiation within some spectral range. For example, a CFA may be

composed of red, green, and blue filters, so that the pixel sensors may provide signals indicative of the visible color spectrum.

If there is not an infrared blocking element somewhere in the optical chain, then infrared radiation (IR), typically considered to be light with a wavelength longer than 780 nm, may also be focused upon the focal plane. Imaging sensors or devices based on silicon technology typically require the use of infrared blocking elements to prevent IR from entering the imaging array. Silicon-based devices will typically be sensitive to light with wavelengths up to approximately 1200 nm. If the IR is permitted to enter the array, the device will respond to the IR, and generate an output image signal. Since the purpose of an imaging system (in this context) is to create a representation of the visible light present in a scene, the IR may introduce a false response and distort the image. In a monochrome (black and white) imaging system, the result may be an obviously distorted rendition. For example, foliage and human skin tones may appear unusually light. In a color imaging system, the introduction of IR may distort the coloration and produce an image with incorrect and de-saturated color.

A common method for preventing these difficulties is to use ionically colored glass or a thin-film optical coating on glass to create an optical element which passes visible light (typically from 380 nm to 780 nm) and blocks the IR. This element can be placed in front of the taking lens, located within the lens system, or it can be incorporated into the imager package. The principle disadvantages to this approach are cost and added system complexity.

An alternative approach is to allow IR to enter the focal plane, and then remove the IR signal electronically. In this approach, the CFA will have some IR pass filters (which also substantially block visible light), and the pixel sensor array would have some pixel sensors responsive to IR only. The effect of IR upon an image signal is substantially reduced by electronically subtracting signals generated by IR pixel sensors from signals generated by pixel sensors responsive to both IR and visible light.

It is therefore desirable to provide for a CFA with a suitable arrangement of IR and visible color filters, and to provide for a method of processing the resulting pixel signals to obtain proper color interpolation without the need of an IR blocking filter.

Brief Description of the Drawings

Fig. 1 illustrates a simplified cross sectional view of an imaging system.

Fig. 2 is a unit array of a four color mosaic pattern for the RGB color space.

Fig. 3 is a circuit diagram of a pixel sensor.

5   Fig. 4 is a signal timing diagram for the pixel sensor circuit of Fig. 3.

Fig. 5 is a flow diagram for color component signal interpolation.

Fig. 6 is a unit array of a four color mosaic pattern.

Fig. 7 is a block diagram of a computer system to perform color interpolation.

Fig. 8 is a unit aray of a four color mosaice pattenr for the CMY color space.

10   ## Detailed Description of Embodiments

A four color Red-Green-Blue-InfraRed (R-G-B-IR) tiling pattern for a CFA is described in which the ratio of green, red, blue, and IR filters is approximately 4:1:1:2. (It may be approximate due to "edge" effects in the deposition of the CFA.) Fig. 2 illustrates a unit array of a tiling pattern according to an embodiment of the present invention, where

15   R, G, B, and IR, denote read, green, blue, and IR pass filters, respectively. The tiling pattern is provided by repeating the unit array of Fig. 2 in both the row and column directions. The number of repetitions may be non-integral. For convenience, we shall refer to IR as a color, so that the tiling pattern based upon the unit array of Fig. 2 is a four-color mosaic pattern. It is also to be understood that the R, G, and B pass filters may also

20   each pass IR.

It is to be appreciated that the designations of rows and columns is arbitrary, and that the pattern of filters in Fig. 2 may be rotated about a perpendicular to the figure. For notational simplicity, we shall denote a pixel sensor as red, green, blue, or IR, if it is responsive to substantially only electromagnetic radiation passed by a red, green, blue, or

25   IR pass filter, respectively.

Let $X(n,m)$ denote the output signal of a pixel sensor responsive to the pass filter of row-column position (n,m). The output signal may, for example, be a voltage or a current. An embodiment of a pixel sensor circuit in which the output signal is a voltage is shown in Fig. 3, where the pixel sensor circuit comprises pixel diode **305** and associated

30   circuitry. Photons captured by diode **305** are measured in the following way. A reset

voltage signal goes HIGH to switch nMOSFET **310** ON so that diode **305** is reverse

biased to a reverse bias voltage V_{cc}. This creates a wide depletion layer within diode **305**.

While reset voltage signal is HIGH, a shutter voltage signal also is set HIGH to switch

nMOSFET **315** ON so that capacitor **320** is charged to the reverse bias voltage of diode

5   **305**. When diode **305** is impacted by a photon with sufficient energy, the photon generates

an electron-hole pair. If the reset voltage signal is brought LOW so that nMOSFET **310** is

OFF but the shutter voltage signal is still HIGH, then electron-hole pairs generated by

photons captured in diode **305** discharge diode's **305** parasitic capacitance, reducing

diode's **305** reverse bias voltage and similarly reducing the voltage stored on capacitor

10   **320**. The length of time for which the shutter voltage signal is HIGH and the reset voltage

signal is LOW determines the integration time. In one embodiment, diode **305** is initially

biased to approximately 2.3 volts.

Fig. 4 illustrates various signals related to Fig. 3. In Fig. 4, the reset and shutter

voltage signals are HIGH during time segment A-B, whereas the reset voltage signal is

15   OFF during time segment B-C but the shutter voltage signal is HIGH. Time segment B-C

represents the integration time. During the integration time, the voltage at the cathode of

diode **305** and the voltage of capacitor **320** are decaying due to the generation of electron-

hole pairs. After the shutter voltage signal goes LOW at time C, the cathode voltage of

diode **305** continues to decay, but the voltage of capacitor **320** stays approximately

20   constant. The voltage difference denoted by V_{image} in Fig. 4, which is the difference

between the initial and final voltages of capacitor **320**, represents the time integration of

the intensity of light captured by pixel diode **305** during a frame time.

To determine V_{image}, the voltage of capacitor **320** needs to be read when diode **305**

is fully reverse biased (when the reset voltage signal is HIGH) and when the shutter

25   voltage signal returns LOW. The voltage of capacitor **320** is read at the source of

nMOSFET **325**, where nMOSFET **325**, current mirror nMOSFETs **330**, and current

source **335** comprise a follower. The source voltage of nMOSFET **325** is read by

switching a row address voltage signal HIGH so that nMOSFETs **340** are ON. If column

line **345** is properly discharged before the row address voltage signal is HIGH, then the

30   voltage on column line **345** is to within a threshold voltage drop of the voltage of

capacitor **320**. Not shown in Fig. 3 are other column pixels coupled to column line **345** and identical in structure to that shown in Fig. 3.

The row address voltage signal is shown in Fig. 4. By setting the row address voltage signal HIGH during the time segment A-B, the source voltage of nMOSFET **325**
5 is read when capacitor **320** is fully charged, and by setting the row address voltage signal HIGH during the time segment C-F (but not at time F) the source voltage of nMOSFET **325** is read when capacitor **320** is discharged after the integration time. The former and latter read source voltages provide calibration and sample voltage signals, respectively. If dark voltage was not present, then V_{image} would be an accurate representation of the time
10 integration of the light intensity incident upon pixel diode **305**. Subtracting the sample voltage signal from the calibration voltage signal compensates for pixel-to-pixel variation, such as differences in threshold voltages for the source follower transistors (nMOSFET **325**).

Fig. 3 is only one representative example of a pixel sensor. The output signals from
15 the pixel sensors are processed to obtain interpolated red, green, and blue color component signals. Let $R(n,m)$, $G(n,m)$, and $B(n,m)$ denote, respectively, interpolated red, green, and blue color component signals for row-column position (n,m).

A method for providing the interpolated color component signals for the tiling pattern of Fig. 2 can be concisely described by introducing the notation that an index i for
20 which $i = 1$, 2, or 3, denotes, respectively, red, blue, or green. As an example of this notation, let $\hat{X}_i(n,m)$ denote an interpolated color component signal, where

$\hat{X}_1(n,m) = R(n,m)$, $\hat{X}_2(n,m) = G(n,m)$, and $\hat{X}_3(n,m) = B(n,m)$. A method for providing the interpolated color component signals for the tiling pattern of Fig. 2 is now described as follows: For a position (n,m), pixel sensor output signal $X(n,m)$, and for
25 each $i = 1$, 2, 3, if $X(n,m)$ is an output signal of a color i pixel sensor, then

$\hat{X}_i(n,m) = X(n,m)$, and if $X(n,m)$ is an output signal of an IR pixel sensor or a color $j \neq i$ pixel sensor, then $\hat{X}_i(n,m)$ is an average of the output signals of nearest neighbor color i pixel sensors.

Fig. 5 provides a flow diagram of the above method. In step **502**, the averaging is understood to be over nearest neighbor pixel sensor positions having color i. To illustrate examples, refer to Fig. 6, which is the tiling pattern of Fig. 2 extended to have five rows. The rows and columns in Fig. 6 are indexed as shown for convenience only. As an example of nearest neighbor averaging, consider position (2,2) in Fig. 6. This is an IR pass filter. A set of interpolated color signal components is:

$$R(2,2) = \frac{X(1,3) + X(3,1)}{2},$$

$$G(2,2) = \frac{X(1,2) + X(2,1) + X(3,2) + X(2,3)}{4}.$$

$$B(2,2) = \frac{X(1,1) + X(3,3)}{2}.$$

As another example, consider position (3,3) in Fig. 6. This is a blue pass filter. A set of interpolated color signal components is:

$$R(3,3) = \frac{X(1,3) + X(5,3)}{2},$$

$$G(3,3) = \frac{X(2,3) + X(3,2) + X(3,4) + X(4,3)}{4},$$

$$B(3,3) = X(3,3).$$

For another example, consider position (3,2) in Fig. 6. This is a green pass filter. A set of interpolated color signal components is:

$$R(3,2) = X(3,1),$$
$$G(3,2) = X(3,2),$$
$$B(3,2) = X(3,3).$$

The above sums and divisions in the above displayed equations are to be interpreted as operations performed in either the analog or digital domain. In general, the averaging of signals over nearest neighbors is approximate because of finite wordlengths, if performed in the digital domain, or the inherent approximate nature of performing operations in the analog domain. Furthermore, the interpolated signals need only be proportional (or approximately) proportional to an average. For example, the right-hand-sides of the above displayed equations may be multiplied by a proportionality factor.

The averaging operations may be performed by non-programmed hardwired circuits (either analog or digital), by circuits programmed by firmware (software stored in

non-volatile memory), by a computer, or any combination of such methods. For example, a simplified computer system is illustrated in Fig. 7. In the embodiment of Fig. 7, processor **702** performs the nearest neighbor averaging indicated in step **502** of Fig. 5, where the software code for performing this averaging is stored in memory **704**. In Fig. 7,

5   camera provides image data to processor **702**. Video interface circuit **708**, which for some embodiments may not be needed, provides for communication between processor **702** and camera **706** via bus **710**. As one alternative to the embodiment of Fig. 7, pixel averaging may be performed by circuits within camera **706**.

Returning to Fig. 5, in step **504**, the indices n and m are changed and new

10   interpolated color component signals are interpolated for a new position (n,m). The processing indicated by Fig. 5 may be performed on the pixel sensor positions in a sequential manner, or more than one position may be processed in parallel.

The output signals from the IR pixel sensors may be used to subtract the IR components from the $\hat{X}_i(n,m)$. For example, an interpolated IR signal component for

15   position (n,m) may be obtained by taking the average of the output signals from the nearest IR pixel sensors, and subtracting this interpolated IR signal from the interpolated color component signals. For some embodiments, this processing may be performed by processor **702**.

The IR pass filters may be manufactured using commercial Color Filter Array

20   (CFA) materials, taking advantage of the fact that these materials are transparent to IR radiation. By a simple overlay of two CFA colors (e.g., R and B pass filters) that have no overlapping transmittance in the visible portion of the spectrum, it is possible to create a composite filter element that blocks the visible light and transmits only IR. If two filters are used to form the composite filter, then each of the two filters has a visible radiation

25   pass spectrum that is disjoint from the other, so that there is substantially no transmittance of visible light through the resulting composite filter formed from the combination of the two filters. If more than two filters are used, then each filter has a visible radiation pass spectrum such that the resulting composite filter is substantially opaque to visible light. This composite filter element is thus an IR pass filter, because each of the component

30   filters used to form the composite filter is substantially transparent to IR.

Another embodiment of the present invention for the CMY (Cyan- Magenta-Yellow) color space is provided in Fig. 8. Fig. 8 denotess a unit array of filters for a tiling pattern, where filters designated by C, Y, and M denote pass filters for the colors cyan, yellow, and magenta, respectively. Note that the unit array of Fig. 8 corresponds ot the

5   unit array of Fig. 2 by making the correspondances: C ↔ B, Y ↔ G, and M ↔ R.

Fig. 5 provides a flow diagram for pixel interpolation with the CMY tiling pattern of Fig. 8, where now $M(n,m)$, $Y(n,m)$, and $C(n,m)$ denote, respectively, interpolated magenta, yellow, and cyan color component signals for row-column position (n,m), and now $\hat{X}_i(n,m)$ denotes an interpolated color component signal where

10     $\hat{X}_1(n,m) = M(n,m)$, $\hat{X}_2(n,m) = Y(n,m)$, and $\hat{X}_3(n,m) = C(n,m)$.

It is to be understood that in some embodiments, not all interpolated color component signals need be obtained by averaging signals from nearest neighbors with like colors. For example, signals from pixel sensors at the edge of the CFA may be processed differently. Or, only a proper subset of the signal outputs from the pixel sensors may be

15   interpolated. Many modifications may be made to the above disclosed embodiments, and the invention is limited only by the scope of the claims below.